Harmonizer

ELECTRICAL & COMPUTER ENGINEERING
UNIVERSITY OF MICHIGAN

EECS 452: Digital Signal Processing Design Lab – Winter 2021

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Introduction

The Harmonizer is a device that allows a single musical performer to sound as if they were a full ensemble. This device is capable of taking in any monophonic signal as an input, and then pitch shifting that signal to user-controlled notes up to 4 times concurrently, all in real-time. This allows a performer to create harmonies on the fly. The ability to harmonize with yourself in real-time is a novel experience for most musicians and thus can provide both inspiration and new possibilities for live performance.

The Harmonizer takes input via a USB MIDI controller plugged into its USB host port, or by way of a computer running MIDI-capable software such as MIDI-OX or Ableton Live. In order to shift a note to a given pitch, the Harmonizer makes use of two algorithms: Time Domain Pitch Synchronous Overlap and Add (TD-PSOLA) and Phase Vocoding (PV).

System Architecture

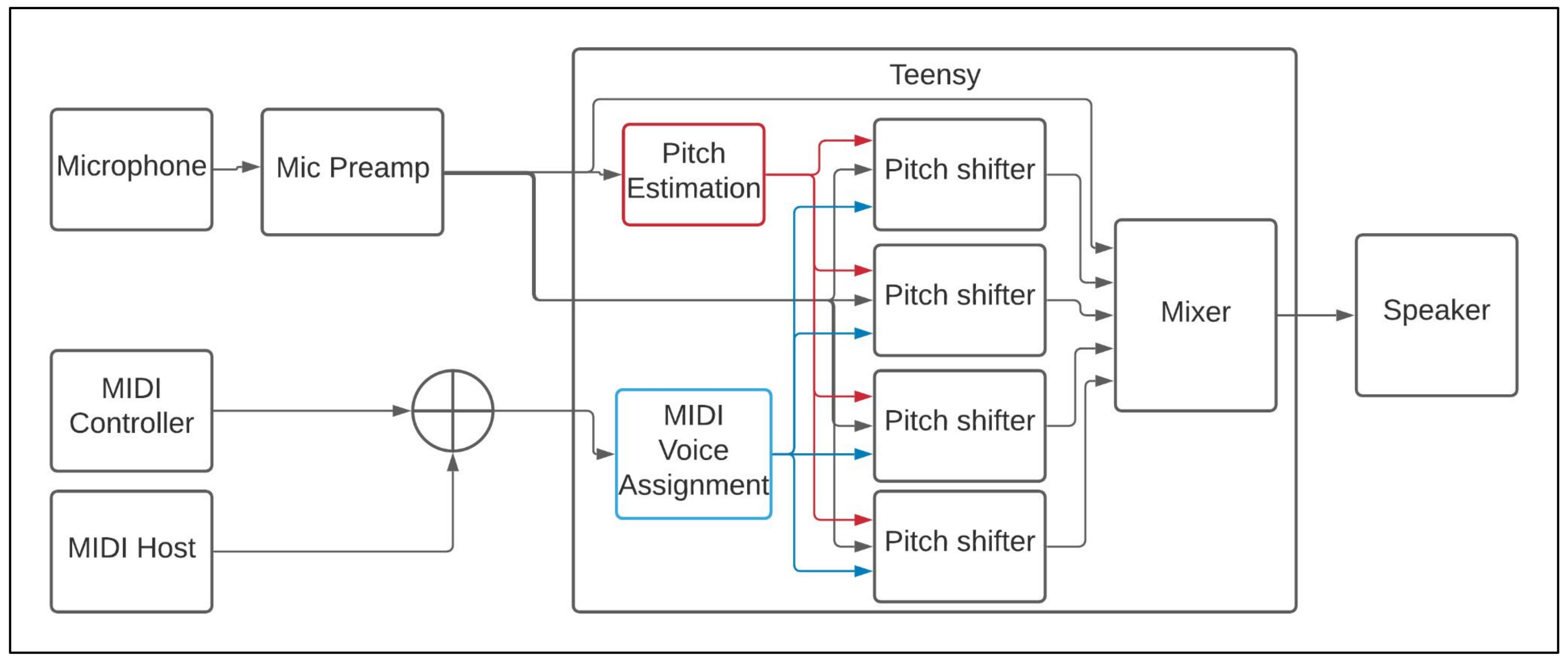

Figure 1: High-level block diagram of the Harmonizer. Inputs are on the left and outputs are on the right.

At the core of the Harmonizer is a Teensy 4.1 equipped with an audio shield, capable of processing audio with a sample rate of 44.1kHz. The Teensy rests on a specialized PCB that provides power to the controller. In addition, the PCB implements a balanced microphone preamp that makes it possible to use professional-grade microphones as input to the device. The preamp also makes use of a second-order low-pass filter to eliminate frequency components above the Nyquist frequency (22.05kHz). This prevents high-frequency noise from interfering with the DSP that takes place on the Teensy.

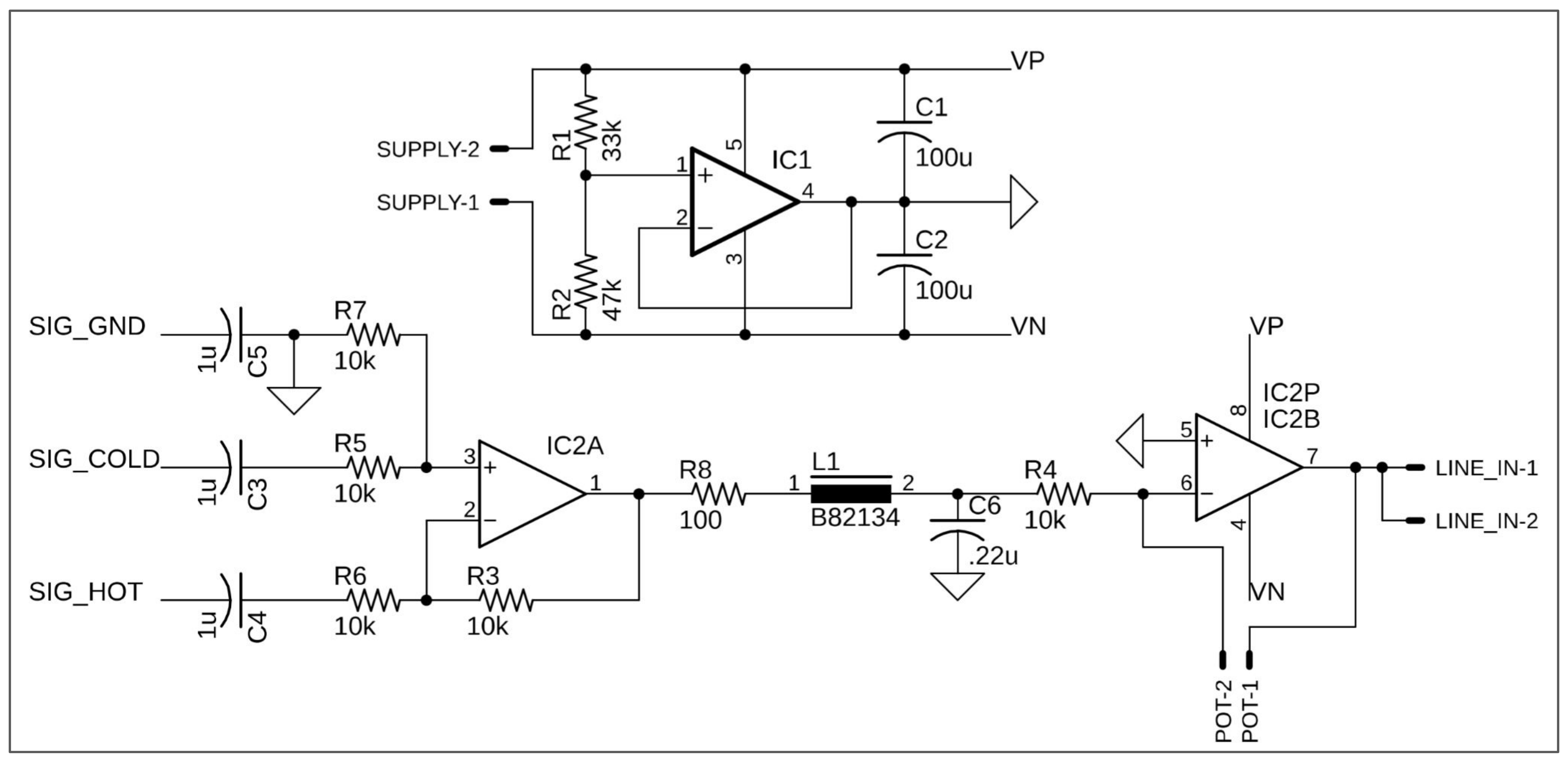

Figure 2: Circuit schematic of preamp and power circuit. Unbalanced input from microphone is converted into a balanced signal for the audio shield.

Algorithms and Techniques

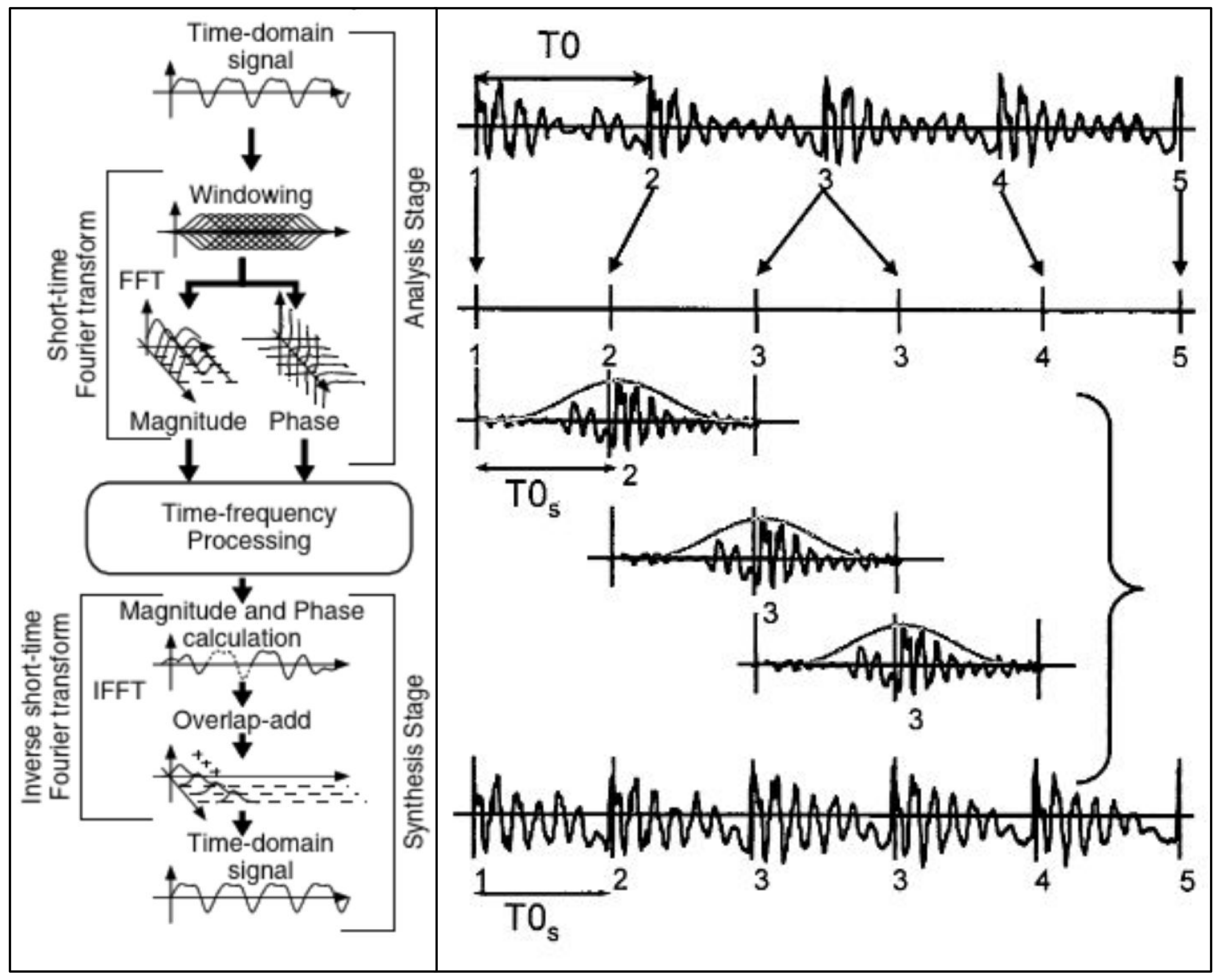

Figure 3: Visualizations of Phase-Vocoding (left) and TD-PSOLA (right).

The Harmonizer uses two algorithms to perform the real-time pitch shifting: Time Domain Pitch Synchronous Overlap and Add (TD-PSOLA) and Phase-Vocoding (PV). TD-PSOLA works in the time domain by adjusting the spacing between the peaks corresponding to the fundamental frequency, while PV works in the frequency domain by synthesizing phase shifted versions of the input to time stretch and then resample the signal. In our device, the signal is pitch-shifted using TD-PSOLA unless it is being shifted down by about an octave or greater, at which point, it is processed using PV.

Innovations

The Harmonizer is implemented in an all-in-one embedded platform to increase accessibility and portability while minimizing the need for time-consuming configuration and expensive software. With onboard class-compliant MIDI methods, the Harmonizer is versatile, able to be controlled with a computer for automation or a keyboard for real-time human interaction.

The Harmonizer has a unique method for blending two pitch shifting algorithms to get the maximum output quality in different frequency ranges. Algorithm transitions depend on the ratio of target frequency to input frequency, known as the shift ratio. Below a shift ratio of 0.5, Phase Vocoding is used. Above a shift ratio of 0.7, TD-PSOLA is used. A crossfade between the algorithms takes place for shift ratios between 0.5 and 0.7.

Challenges inherent to the project included ensuring a processing speed high enough to be able to compute and playback the altered signal with the real-time input. A sharp tone change in the input causes a slight delay with the harmonized outputs.

Acknowledgements

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Results and Findings

To test the effectiveness of the shifting algorithms, a tritonal sinusoidal signal comprised of equal-magnitude harmonic components at f_0=261.63 Hz, $f_1=2*f_0$, and $f_2=3*f_0$ was fed into the Harmonizer for a total of 49 seconds. In intervals of one second, the harmonizer was sent shift targets in the form of MIDI notes representing semitones from 65.41 Hz (C1) to 1046.50Hz (C5), a total of 49 individual notes spanning four octaves. The results were compared against the frequency spectrum of tritonal sinusoids generated with f_0 in the same range.

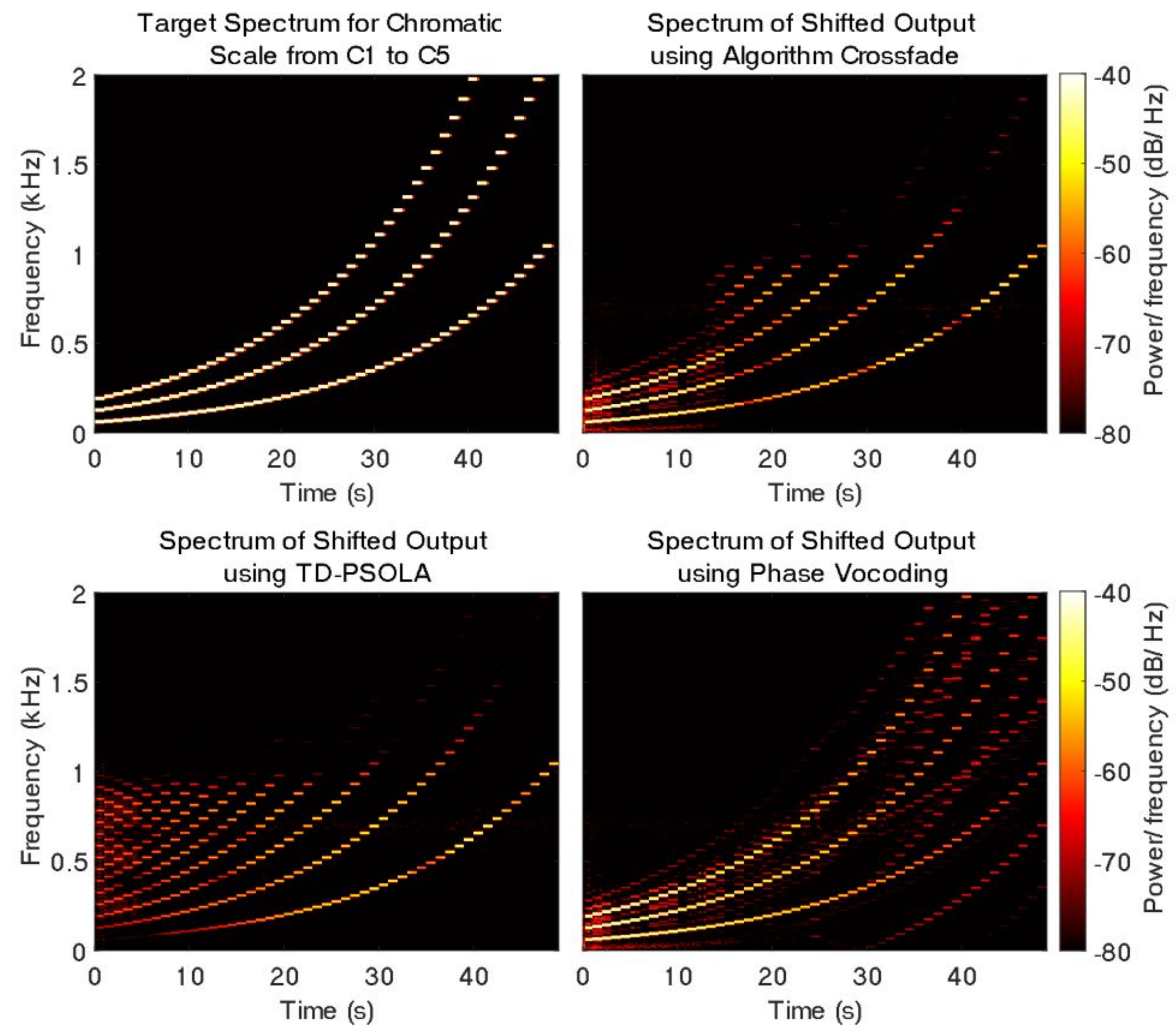

Figure 3: Spectrograms of synthesized target output frequency spectrum (top left), TD-PSOLA shifted signal (bottom left), Phase Vocoding shifted signal (bottom right), and crossfading method (top right).

Testing revealed that Phase Vocoding is ideal for lower frequencies due to attenuation of the low frequencies for shift ratios below 0.5 when using TD-PSOLA. On the contrary, TD-PSOLA is ideal for higher frequency components due to less aliasing as compared to Phase Vocoding.

The performance of the shifting algorithms was tested by measuring the elapsed time while processing a block of 1024 samples on the Teensy 4.1. TD-PSOLA takes an average of 50 microseconds while Phase-Vocoding takes an average of 5317 microseconds. Phase-Vocoding is just fast enough to run 4 concurrent shifts.

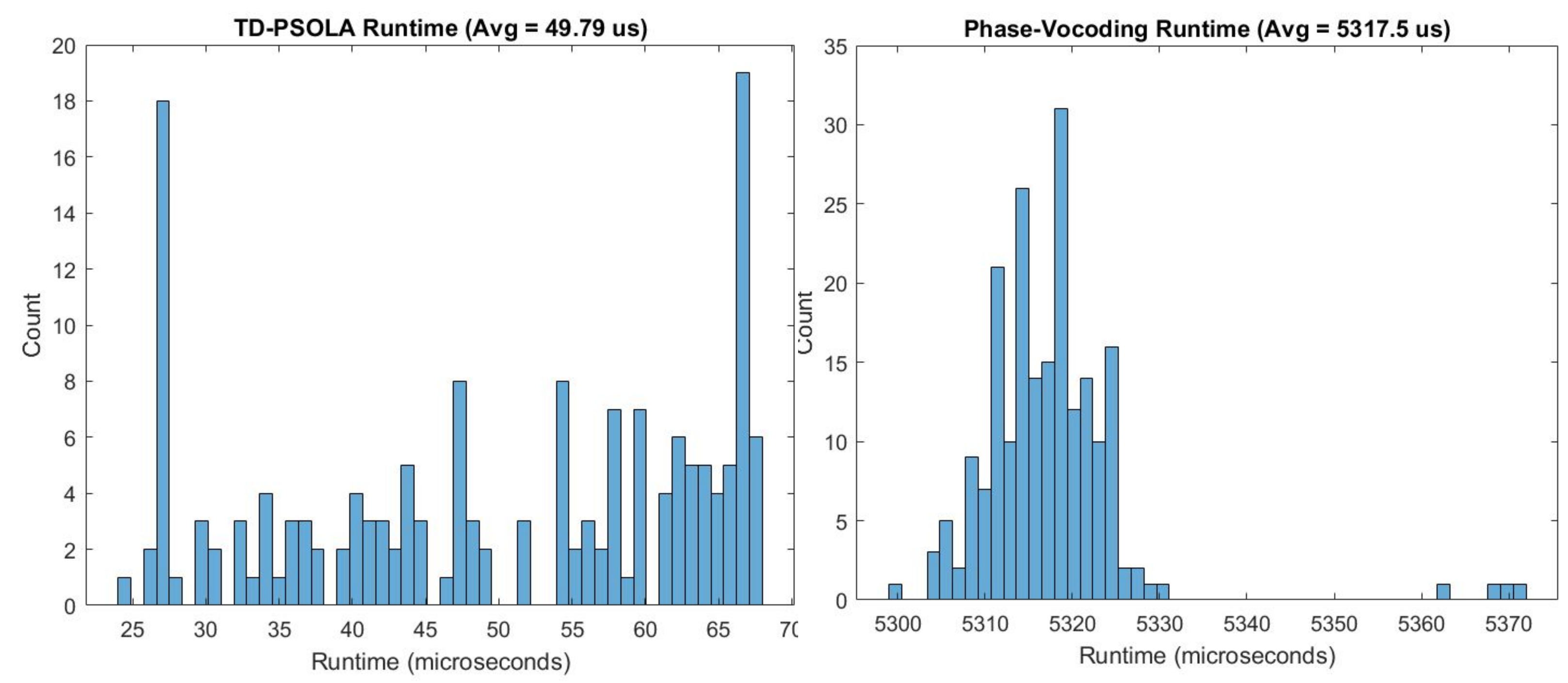

Figure 5: Runtime measurements of TD-PSOLA (left) and Phase-Vocoding (right).